ISOCAM* Observations of NGC 6946: Mid-IR Structure

S. Malhotra,[1], G. Helou[1], D. van Buren[1], M. Kong[1], C. A. Beichman[1], H. Dinerstein[3], D. J. Hollenbach[4], D. A. Hunter[5], K. Y. Lo[6], S. D. Lord[1], N. Y. Lu[1], R. H. Rubin[4], G. J. Stacey[7], H. A. Thronson Jr.[8], and M. W. Werner[9]

[1] IPAC, California Institute of Technology, MS 100-22, Pasadena, CA 91125
[2] ESA Villafranca Satellite Tracking Station, Apartado 50727 28080 Madrid, Spain
[3] University of Texas, Astronomy Department, RLM 15.308, Texas, Austin, TX 78712
[4] NASA/Ames Research Center, MS 245-6, Moffett Field, CA 94035
[5] Lowell Observatory, 1400 Mars Hill Rd., Flagstaff, AZ 86001
[6] University of Illinois, Astronomy Department, 1002 W. Green St., Urbana, IL 61801
[7] Cornell University, Astronomy Department, 220 Space Science Building, Ithaca, NY 14853
[8] University of Wyoming, Wyoming Infrared Observatory, Laramie, WY, 82071
[9] Jet Propulsion laboratory, MS 233303, 4800 Oak Grove Rd., Pasadena, CA 91109

Received August 7 1996; accepted

Abstract. The nearby spiral galaxy NGC 6946 was observed with ISO-CAM in the mid-infrared, achieving 7" resolution and sub MJy sr^{-1} sensitivity. Images taken with CAM filters LW2 (7μm) and LW3 (15μm) are analysed to determine the morphology of this galaxy and understand better the emission mechanisms. The mid-infrared emission follows an exponential disk with a scale length 75". This is 60% of the scale length in the optical R-band and about half the scale length of the radio continuum. The nuclear starburst region is too bright for reliable measurement in these images. Its surface brightness exceeds 12 to 15 times that in the inner disk. The arms and interarm regions are clearly outlined, with each of these components contributing about equally to the disk emission. The arm-interarm contrast is 2-4 in the mid-IR, close to that measured in the visible R band light and lower than the contrast in $H\alpha$, suggesting that non-ionizing radiation contributes significantly to dust heating.

Key words: Infrared - galaxies; Galaxies - individual; Galaxies -- Morphology

Send offprint requests to: san@ipac.caltech.edu

* Based on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) and with the participation of ISAS and NASA.

1. Introduction

NGC 6946 is a nearby face-on spiral galaxy, a good target for a study of star-formation and related processes in "normal" galaxies. In addition to the well-resolved disk, it has a starburst nucleus (e.g. Engelbracht et al. 1996), and a bright northern spiral arm that earned it an entry in the Atlas of Peculiar Galaxies (Arp 1966). NGC 6946 was therefore selected as a focus of the ISO (Kessler et al. 1996) Key Project under NASA Guaranteed Time on the interstellar medium of normal galaxies (Helou et al. 1996). We report here on the ISO-CAM (Cesarsky et al. 1996) maps obtained for this galaxy, revealing for the first time the mid-infrared (MIR) morphology at vastly improved resolution and sensitivity.

MIR emission in the 5 to 20 μm range is dominated by very small grains fluctuating to high temperatures and from Poly Aromatic Hydrocarbons (PAH) features. Even though these grains are not in thermal equilibrium, they still convert heating photons (Draine and Anderson 1985), and should therefore trace star forming regions, allowing a detailed and un-extincted view of that activity. By studying the distribution of the MIR emission with respect to other components of the galaxy, i.e. HI, H_2, ionized gas, and starlight we can also characterize the heating sources for the MIR, and better define its diagnostic value.

2. Observations and Data reduction

NGC 6946 was mapped at 7μm (LW2 filter, $\Delta\lambda = 3.5\mu$m) and at 15μm (LW3 filter, $\Delta\lambda = 6\mu$m), using the raster scan mode to cover roughly $12.5' \times 12.5'$ centered on the nucleus. CAM was set to 6″/pixel, and the raster was made up of 8×8 pointings separated by 81″, or 13.5 pixels in each direction, allowing for better spatial sampling. At each pointing in the raster scan we took 8 frames integrating 5 seconds for each at 7 μm and 10 frames of 2 seconds each at 15 μm. Hα and broad-band imaging of NGC 6946 was done at Palomar 60-inch telescope.

The first step in reducing the ISO CAM data was deglitching, done within the ISOCAM Interactive Analysis package using the routine "mr1d deglitch", found most reliable among the available procedures for removing cosmic ray hits. Detector transients were then removed within the same software package, using the transient removal algorithm based on the "IPAC" method, which uses a simplified physical model for each pixel's time dependent behavior. Then a set of eight "local" flat fields were constructed by taking medians of sequential galaxy-free frames and were then used to form interpolated flats for each of the individual frames, using a simple linear interpolation scheme for each pixel. The dark-removed, deglitched and transient corrected data were then flattened by dividing each frame by the appropriate interpolated flat field. Using these processed data we then constructed a model for the sky flux distribution in an array with $3'' \times 3''$ pixels. This finer array is required because the raster steps amount to 13.5 of the $6'' \times 6''$ camera pixels. We assumed the raster steps correspond exactly to commanded values. A least squares fit was then made to determine the maximum likelihood value of the sky's average surface brightness in each pixel. This scheme of modelling the sky avoids some of the error propagation problems of the more traditional means of producing mosaiced images (cf van Buren and Kong, 1996).

The diffraction-limited beam of ISO has a FWHM of 3″ at 7μm and about 6.3″ at 15μm, but this resolution is not achievable with our observing mode. In the 7 μm image we see two foreground stars whose FWHM measures about 7.3″. At 15μm the stars are very faint, and only one of them has a measurable FWHM of 7.2″. The noise levels in these images are approximately 0.1 MJy sr^{-1} $\sim$ 2μJy arcsec^{-2}, approximately 3 times lower than the noise in the "Auto Analysis Results" map (OLP4.0). Features roughly a thousand times brighter are still reliably measured in these maps. The inner 15″ or so are too bright to measure, and the surface brightness at the nucleus exceeds 300 and 560 MJy sr^{-1} respectively in LW2 and LW3.

These maps result from a preliminary data reduction which could be significantly improved, especially in the areas of transient removal and flat fields.

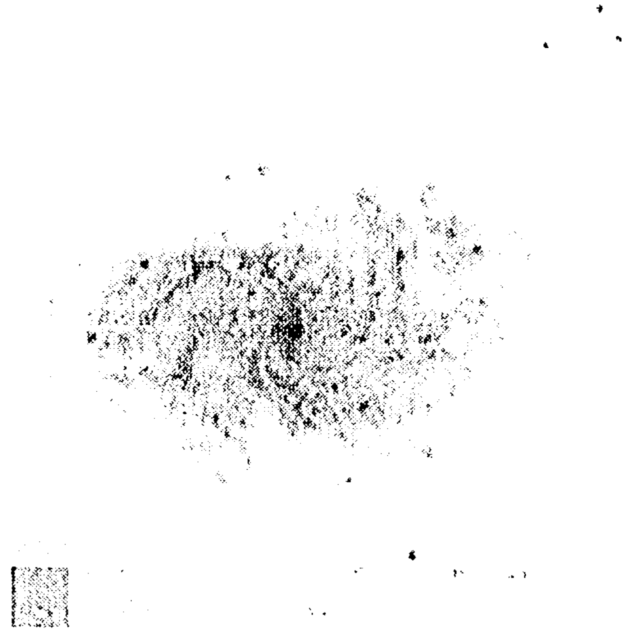

Fig. 1. ISOCAM image of NGC 6946 in the LW2 filter at a wavelength of 7μm, $\Delta\lambda$ = 3.5μm. This image is a mosaic of 8×8 pointings aligned with the major axis. Log scale of brightness is used to display the dynamic range of the exponential disk surface brightness. Some Galactic foreground stars are visible to the south and west of NGC 6946. Fortuitous alignment of several features produce what seems to be an "edge" parallel to the major axis in the north. This is at least partly real and visible in optical images, and is exaggerated by residual responsivity drifts unaccounted for by the time-dependent flat field.

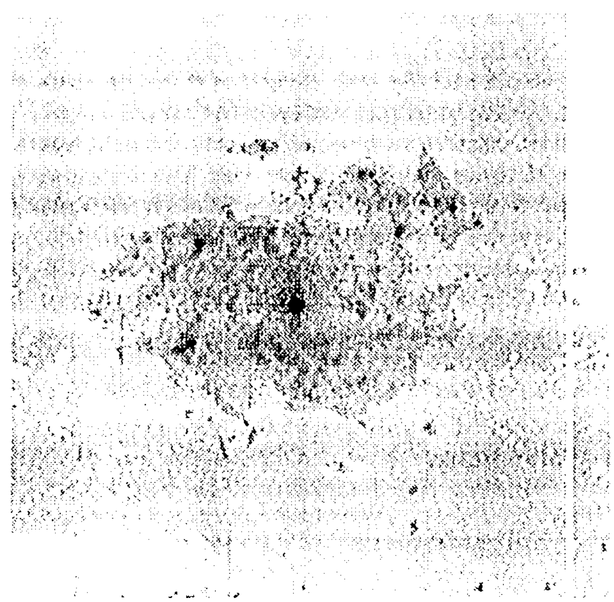

Fig. 2. ISOCAM image of NGC 6946 in the LW3 filter at a wavelength of 15μm, $\Delta\lambda$ = 6μm. This image is a mosaic of 8×8 pointings.

3. Disk Structure

The ISOCAM maps of NGC 6946 have enough resolution, sensitivity and extent to allow a detailed comparison with the maps at other wavelengths. The Mid-IR images at both wavelengths show a good qualitative similarity to optical, radio and $H\alpha$ images. Diffuse emission from the disk in the interarm regions is clearly detected (Figures 1 and 2) and can be traced out to $\sim 5'$, comparable to the visible-light size of $10' \times 12'$.

Except for the region in the inner $50''$ of the galaxy where oval distortions are present (Zaritsky & Lo 1984), the Mid-IR light follows an exponential profile (Figure 3). The radial profile of the galaxy is calculated by first de-projecting the galaxy to the plane of the sky, subtracting the mean sky from an annulus outside the galaxy and then taking median emission levels at different annuli. By taking the median emission in an annulus instead of the mean we minimize contributions from very bright regions of the spiral arms. Both LW2 and LW3 images were analysed in this manner and snow identical scale lengths of 75" at radii between 70" and 200". This scale length is mildly dependent on range of radii where the fit is taken, and on the sky subtraction; we estimate the uncertainty at about 10%

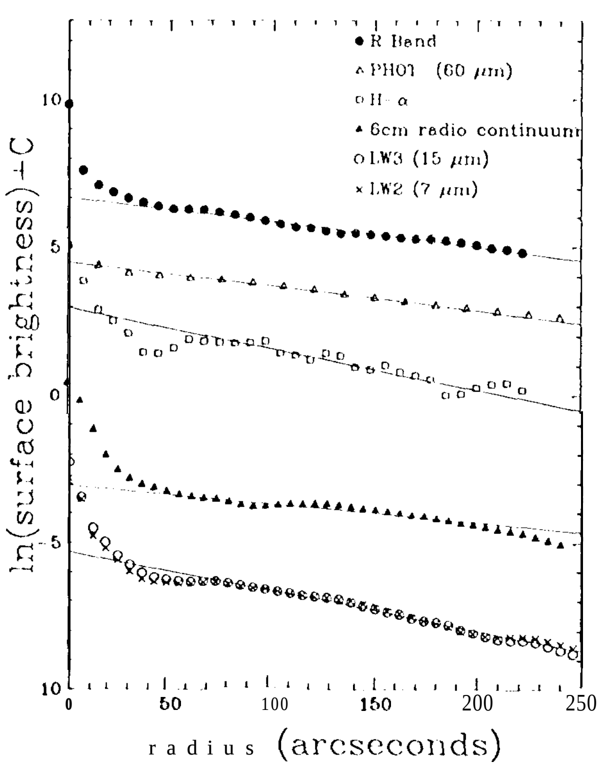

Fig. 3. The radial profile of NGC 6946 is exponential at most wavelengths including the Mid- Infrared, but with different scale lengths. Here we show the exponential profiles seen with LW2, LW3 filters of ISOCAM, radio (6 cm), $H\alpha$, Far-Infrared (60pm) (with ISOPHOT) and Optical R band images for comparison

For comparison we derive scale lengths for the optical R-band, $H\alpha$, and 6 cm radio continuum emission using the same method as for the mid-infrared emission. The results are listed in Table 1. Also listed are scale-lengths derived by previous studies of this galaxy. We see that the mid-infrared emission and $H\alpha$ emission have similar scale-lengths closest to the scale length of CO distribution of 86" (Tacconi & Young 1986, TY86). Red light in optical I and R bands shows a scale length of 125" and $115''$. To reconcile the optical and mid-infrared scale lengths we need to have made in the CAM images a sky subtraction error about ten times greater than the pixel-to-pixel rms noise. The ratio of mid-infrared to radio behaves much like the ratio of far-infrared to radio, falling by the expected factor of 2 from a radius of 100" to 200" (Lu et al. 1996).

Table 1. Scale lengths

Wavelength	scale length	range of fit	Source
7 μm	$74.6''$	70- $200''$	this paper
15 μm	$74.6''$	70- 200"	this paper
$H\alpha$	71.9"	70 - 200"	this paper
6 cm continuum	158.6"	70- 200"	this paper
R-baud (0.70 μm)	115.9"	70- 200"	this paper
60 μm	121.9"	70- 200"	this paper
HI (21 cm)	294"	200- $580''$	TY86
H_2	$86''$	40- 280"	TY86
Total ISM (HI+H_2)	112"	40-280"	TY86

4. Arm-Interarm Contrast

One of the striking features of the ISO-CAM maps of NGC 6946 is the conspicuous diffuse disk underlying the arms, The disk is relatively symmetric, making it, unlikely to be the result of transient effects in detectors or other artifacts. In a semi-flocculent galaxy like NGC 6946 it is difficult to quantify the arm-interarm contrast. We define this contrast as the ratio between the peak in the arms and the median value of brightness in an annulus at, that radius. The arm regions were selected from the maps by eye. The contrast varies between 2 and 4 with the northern arm showing a higher arm brightness. The arm-interarm contrast rises from 2 to 4 with increasing radius along the northernmost arm (Figure 4). The southernmost arm is not continuous and shows arm-interarm contrast between 1 and 2 in the, inner parts of the galaxy and up to $\sim$4 in the outer section which is disjointed (Figures 1 and 2). These results are consistent with TY86 who find that the arm-interarm ratio in CO emission increases with radius.

Comparison of the arm-interarm contrast between mid-infrared and $H\alpha$ emission could address the issue of what heats the dust, and more specifically whether it is the ionizing radiation which is responsible for the mid-infrared emission (Devereaux & Young 1993) or whether diffuse soft UV and visible starlight plays a significant role (Persson & Helou 1987). If the dust heating is primarily from ionizing radiation, the mid-infrared emission should follow the distribution of ionized gas as traced by $H\alpha$ for example. The data in hand (Figure 4) suggest that the arm-interarm contrast is higher for $H\alpha$ than for the mid-IR. Since our $H\alpha$ images do not detect interarm emission, our estimate of the discrepancy in contrasts is only a lower limit. The $H\alpha$ and Mid-lit emission have similar scale lengths in the disk as shown in the previous section, whereas they have dissimilar arm-interarm contrast, The arm-interarm contrast in Mid-lit is closer to the contrast in R band light, which has a much longer scale length than mid-IR or $H\alpha$. One explanation may be that the PAHs are destroyed near 1111 regions in the arms, thus softening the contrast between arms and interarms.

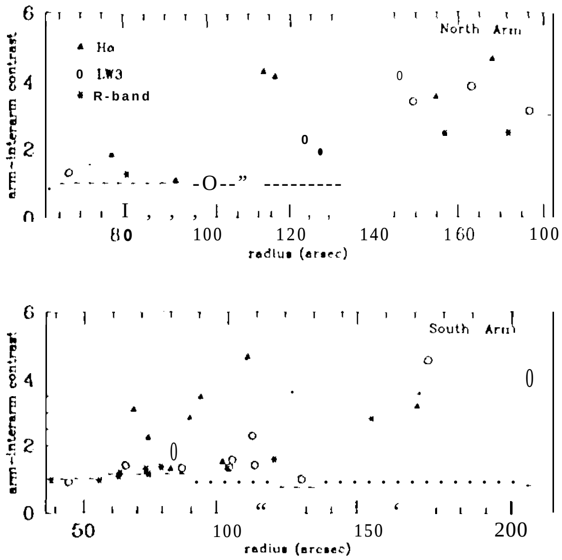

Fig. 4. The Arm-Interarm contrast (defined in §4) is plotted as a function of radius for the northern and the southern arms. The triangles represent the $H\alpha$ arm-interarm contrast and the open circles show the contrast for LW3 (15μ m) image.

5. Nucleus

Various indicators point to NGC 6946 as having a starburst nucleus (e.g. van der Kruit, Allen & Rots 1977, Rieke 1976; Telesco & Harper 1980; DeGioia-Eastwood et al. 1984). The starburst nature of the nucleus is confirmed by the ISOCAM data, which show a greatly enhanced surface brightness, measuring 12 and 18 times the surface brightness of the nearby inner disk in LW2 and LW3 filters respectively (Figure 3). Because the nucleus reached beyond the linear regime of the CAM detector in these data, these values must be taken as lower limits to the surface brightness of the nucleus. Telesco, Dressel & Wolstencroft 1993 measure the peak brightness at $10.8\,\mu$m to be 0.4 Jy. The size of the nucleus is measured to be 100 pc at 10 μm (Telesco et al. 1993) and 8″ (~ 200 pc) at 6 cm continuum Beck & Hoernes (1996)

6. Conclusion

Based on this preliminary reduction of ISO-CAM data, it is clear that the ~llid-infrared morphology of NGC 6946 is quite distinct from other traditional tracers of the interstellar medium, and a promising addition because it, is largely free of extinction. The maps clearly show the familiar structure of arms, exponential disk, and high brightness star-burst nucleus. However, they also suggest that the mid-infrared may be a more complex tracer, which is closest to $H\alpha$ in disk scale length, but resembles most the visible R band io arm-interarm contrast. The mid-infrared emission is not distributed like atomic gas which has a hole in the center (TY86) nor like total gas distribution, but its radial profile is similar to that of molecular gas. Though puzzling and subject to more thorough data reduction and analysis, these statements are not necessarily contradictory, since each of the tracers is a product of physical quantities modified by several effects,

Acknowledgements. This work was supported by ISO data analysis funding from the US National Aeronautics and Space Administration, and carried out at the Infrared Processing and Analysis Center and the Jet Propulsion Laboratory of the California Institute of Technology.

References

Arp, H, 1966, ApJS, 14, 1.

Beck R. & Hoernes, P., 1996, Nature 251,15

Cesarsky et al., 1996, A&A, this issue.

DeGioia-Eastwood, K., Grasdalen, G.L., Strom, S.E., Strom, K.M, 1984, ApJ, 278, 564

Devereaux, N. A., Young, J., 1993, AJ 106, 948.

Draine, B.T., Anderson, N. 1985, ApJ, 292, 494.

Engelbracht, C. W., Rieke, M, Rieke, G.H., Latter, W., 1996, ApJ in press.

Helou et al. 1996, A&A, this issue.

Kessler et al. 1996, A&A, this issue.

Lonsdale Persson, C. A., Helou, G.X., 1987, 314, 514

Lu N et al., 1996, A&A, this issue.

Rieke, G.H., 1976, ApJ, 206, L15

Tacconi, L., Young, J., 1986, ApJ, 308, 600.

Telesco, C. M., Dressel, L.L., Wolstencroft, R.D., 1993, ApJ 86, 286

Telesco, C. M., Harper, D.A., 1980, ApJ, 235,392.

van Buren, D., Kong, M., 1996, A&A, this issue.

van der Kruit, P., Allen, R., Rots A.H. 1977, A&A, 55, 421.

Zaritsky, D., Lo, K.Y., 1986, ApJ, 303, 66.

This article was processed by the author using Springer-Verlag LaTeX A&A style file L-AA version 3.